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Seismic Sequence Stratigraphy Analysis Using Signal Mode Decomposition

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Summary

Reflecting depositional events, sequence stratigraphy can be commonly observed, and mapped on seismic amplitude volumes, but it is also often masked by noise and artifacts from acquisition and processing. Signal decomposition techniques can reveal hidden features in the seismic data. In this paper, we adopt a novel data-driven signal mode decomposition method, variational mode decomposition (VMD), to characterize the stratigraphy boundaries. Synthetic depositional model example shows that the decomposed modes can capture different order depositional trends. The field application in Dutch Sector, North Sea, demonstrates that adaptive mode decomposition method can effectively delineate the stratigraphic sequences.

Introduction

Signal decomposition methods decompose seismic data into different spectral components, or predefined mother wavelets, or modes derived from the data itself. Because seismic signal has varying spectral components along the traces and depth, it need to be analyzed as a non-stationary signal with time frequency analysis (TFA) methods (Han and van der Baan, 2013) rather than Fourier transform, which is a stationary signal analysis method. Traditionally, most seismic decomposition methods have been constrained by predefined parameters. Whereas, the subsurface has been built over geologic time through deposition, deformation, erosion, and diagenesis, there would be a conflict between the "actual" features and human defined expressions.

Huang *et al.* (1998) proposed empirical mode decomposition (EMD) to analyze non-stationary signal without any priori knowledge. The intrinsic mode functions (IMF) can model the inherent nonstationarity and nonlinearity of the data. However, EMD carries out in time domain and not based on bandlimited assumption, so it suffers the mixed frequency problem. Dragomiretskiy and Zosso (2014) developed variational mode decomposition (VMD) to decompose an input signal into an ensemble of band-limited IMFs in frequency domain.

The depositional events in a certain geological time period can be represented on the seismic amplitudes within a certain spectral bandwidth. However, because of the existence of interferences in the seismic data, sometimes it is difficult to divide the sedimentary cycle correctly. Mode decomposition is a kind of data-driven method, and capable of decomposing non-stationary signals into highlight different intrinsic modes. In this way, the sequence stratigraphy information can be obtained directly from seismic data. Though we can also get the sedimentary information by processing the logging data, logging materials besides the well points cannot cover the whole survey, which makes seismic data more suitable for large scale geological facies analysis.

In this paper, we adopt VMD for sequence stratigraphy analysis. First, we briefly introduce principles of VMD. Then, based on a synthetic sedimentary model, we show VMD's capability in sedimentary pattern recognition. Later, a field application of deltaic facies shows that the data-driven mode decomposition method distinguishes depositional sequences and delineate the stratigraphic boundaries.

Variational Mode Decomposition (VMD)

Huang *et al.* (1998) proposed EMD to decompose a data series into a finite set of IMFs, which represent different oscillations embedded in the data. Through a sifting process in time domain, IMF is obtained, but the band-limited property cannot be assured. While, VMD decomposes an input signal into a number of elementary amplitude/frequency modulated harmonics, which have specific sparsity properties (Dragomiretskiy and Zosso, 2014). The IMFs are extracted concurrently instead of recursively in the frequency domain. VMD is achieved by solving the following optimization problem:

$$\begin{aligned} &\min_{\{u_k,\ \omega_k\}} \left\{ \sum_k \left\| \partial_t \left[\left(\delta(t) + \frac{j}{\pi t} \right) * u_k(t) \right] e^{-j\omega_k t} \right\|_2^2 \right\}, \\ &s.\ t. \quad \sum_k u_k = s(t) \end{aligned} \tag{1}$$

where u_k and ω_k are modes and their central frequencies, respectively. $\delta(\bullet)$ is a Dirac impulse. $s(t)$ is the signal to be decomposed with the constraint condition that the summation over all modes should be the input signal. The term $\left(\delta(t) + \frac{j}{\pi t} \right) * u_k(t)$ is the Hilbert transform of u_k.

Dealing with single trace decomposition, VMD results can't keep the lateral consistency of the whole seismic section. For field applications, the seismic data reflect underground geology information, which requires the decomposition results consistent laterally in processing and interpretation. To solve this problem, Li *et al.* (2016) added lateral consistency constraint in the optimization object function, then the consistency preserved VMD is achieved by solving the following problem:

$$\begin{aligned} &\min_{\{u_k,\ \omega_k\}} \left\{ \sum_k \left\{ \left\| \nabla \left[u_{k,A}(\vec{t}) e^{-j\langle \vec{\omega}_k, \vec{t} \rangle} \right] \right\|_2^2 + \left\| \mathbf{P}_s u_{k,A}(\vec{t}) \right\| \right\} \right\}, \\ &s.\ t. \quad \sum_k u_k(\vec{t}) = s(\vec{t}) \end{aligned} \tag{2}$$

where ∇ is the gradient operator, $u_k(\vec{t})$ are the 2D modes, and their analytic formats are $u_{k,A}(\vec{t})$. $\overrightarrow{\omega_k}$ are the central frequency vectors. $s(\vec{t})$ is the vertical seismic section to be decomposed in the seismic application. $\mathbf{P}_s$ is the 2D Wiener prediction filter based on $u_{k,A}(\vec{t})$.

Synthetic Depositional Sequence Model

Sequence stratigraphy interpretation can be made based on rock composition, grain size characteristics, spontaneous potential, and gamma ray log shapes. Following Rider (1999), we build a depositional cycle model: delta progradational model. The thickness of sandstone increases upward, and the grain size of sediment changes from fine to coarse, and the sandstone is interbedded with similar thick shale layers. The Gamma Ray log, which decreases upward, and depositional settings are shown in Figure 1. Figure 2 shows the synthetic reflectivity series and seismic traces. The synthetic trace is 60ms long. The reflectivity series follow the same pattern in Figure 1, and because the grain size changes, the seismic reflectivity between shale and sandstone also changes with depth. We apply VMD on the synthetic seismic data. The IMF-1, IMF-2, and IMF-3 are shown in Figure 2. Note the IMF-1 shows the same trend with the Gamma Ray log in Figure 3.

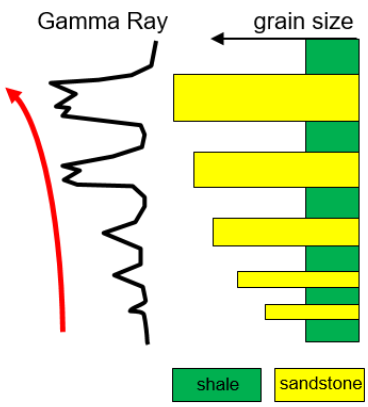

Figure 1 *Gamma Ray log shape and depositional setting of deltaic progradational depositional trends, modified from Rider (1999).*

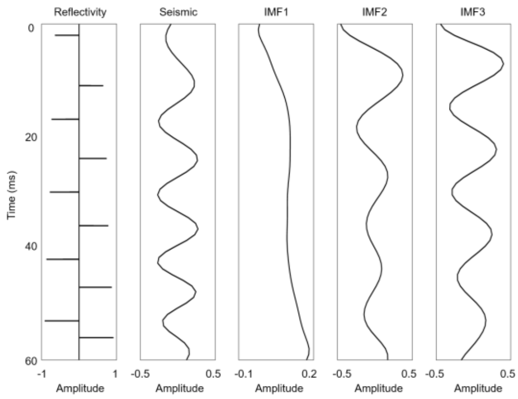

Figure 2 *Reflectivity series, seismic traces and IMF-1, IMF-2 and IMF-3 of the delta progradational model in Figure 1. The amplitude of IMF-1 decreases upward like the Gamma Ray log in Figure 1.*

Field Application

The field seismic data set is from Dutch Sector, North Sea. Figure 3a shows a vertical seismic section. The deltaic cycles in Dutch sector rang from a river-dominated to a wave-tide dominated stages. These cycles are comprised of classic clinoform geometries prograding towards the basin (Petruno et al., 2015). Figure 3b shows sequence stratigraphy interpretation. Based on the recognition of seismic reflection termination patterns (toplap, onlap, downlap and truncation, shown in Figure 3b), five regional and local subaerial unconformities, two maximum regressive surface, two maximum flooding surface and three basal surface of forced regression are defined by the seismic sequence stratigraphic techniques. Based on sequence boundaries, positon and parasequence stacking pattern, the Pliocene strata of study area is divided into four third order sequences. Furthermore, a complete depositional sequence is divided into four system tracks: Lowstand Systems Tracts (LST), Transgressive Systems Tracts (TST), Highstand Systems Tract (HST) and Falling Stage Systems Tract (FSST).

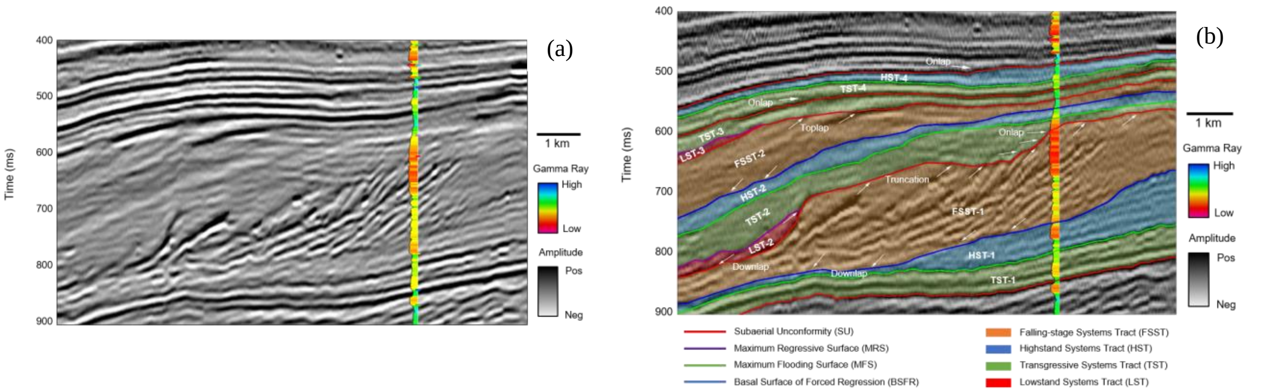

Figure 3 *One seismic section perpendicular to shoreface direction (a) without, and (b) with sequence stratigraphy interpretation. Based on recognized isochronous stratigraphic interfaces, the Pliocene strata are divided into four third-order sequence (SQ). From the onset of base level rise to the end of base level fall, one complete base level cycle is divided into four stages, LST, TST, HST, and FSST. SQ-1 and SQ-2 contain relative complete system tracts, SQ-3 and SQ-4 only retain the strata records of base level rising because of regional erosion. The Gamma Ray log is shown.*

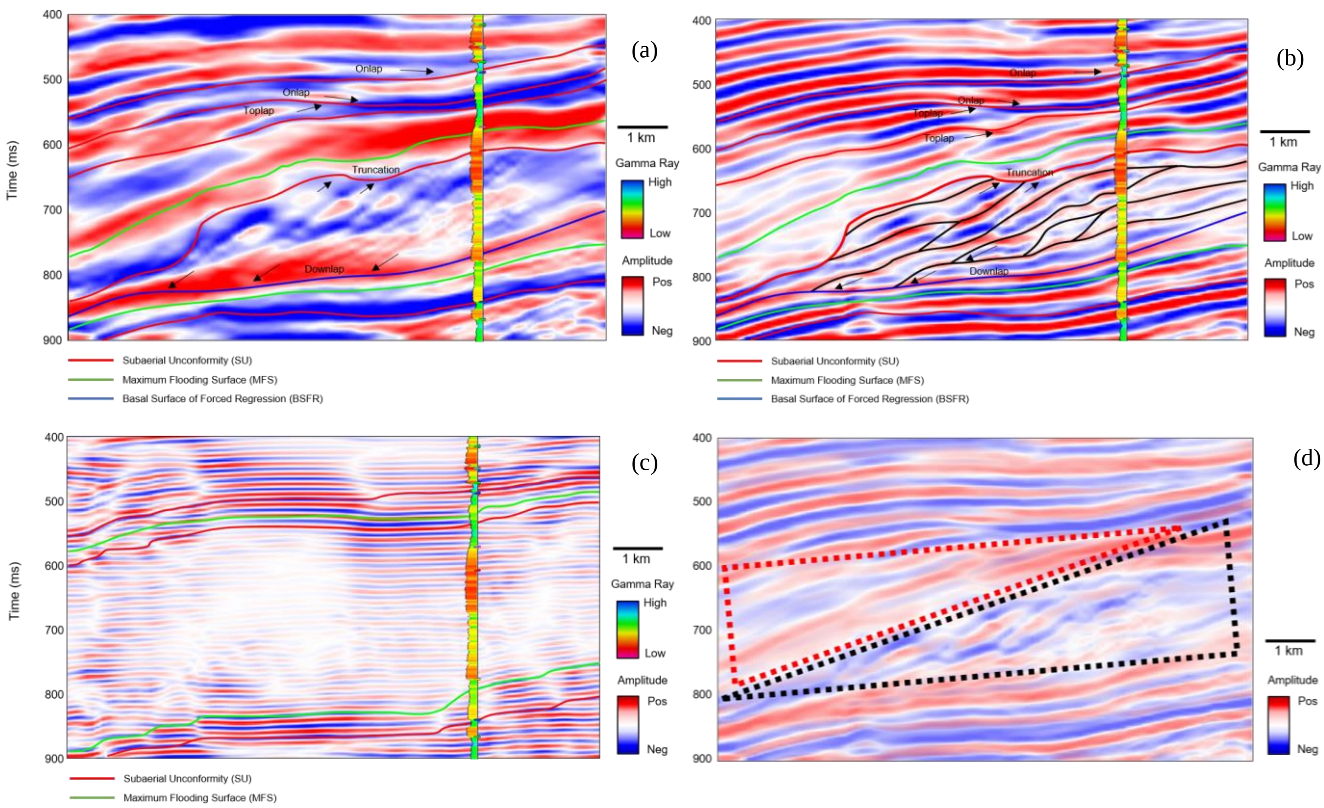

Figure 4 *Sequence stratigraphy interpretation on (a) IMF-1, (b) IMF-2, and (c) IMF-3, corresponding to Figure 3b. The high amplitudes on IMF-1 highlight SUs, MFSs and BSFR. Stratigraphy terminations are clear in both IMF-1 and IMF-2, with the clinoform more clearly imaged by IMF-2. The SUs and MFSs exhibit high amplitudes on IMF-3, but the stratigraphy details seen in IMF-1 and IMF-2 are not clear. (d) By blending addition IMF-1 and IMF-2, one can delineate the two depositional sequences, SQ-1 and SQ-2 (dotted triangle).*

We apply VMD on the seismic data. On Figure 4, stratigraphic terminations, such as onlap, toplap, downlap, and truncation, are labelled, like Figure 3b. In Figure 4a, the subaerial unconformities (SUs), maximum flooding surfaces (MFSs) and basal surface of forced regression (BSFR) show strong energies. We can also observe the onlap, toplap, downlap, and truncation features. In Figure 104, the onlaps, toplaps and downlaps are very clear, as well as the stratal clinoforms, which is low amplitude and hard to observe on Figure 3a. The SUs and MFSs show high amplitudes on IMF-3. Though the stratigraphy details are not clear on Figure 4c, we can have a rough conception where is the clinoform. In Figure 4d, IMF-1 and IMF-2 are color blended together. Two depositional sequences, SQ-1 and SQ-2, show up more clearly, compared to the original seismic section. Thanks to the new details, the VMD does assist the stratigraphy interpretation.

Conclusions

We investigate seismic stratigraphy based on VMD. As an adaptive data-driven method, VMD provides valuable information for stratigraphy interpretation. The modeling test and field application show very encouraging results.

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